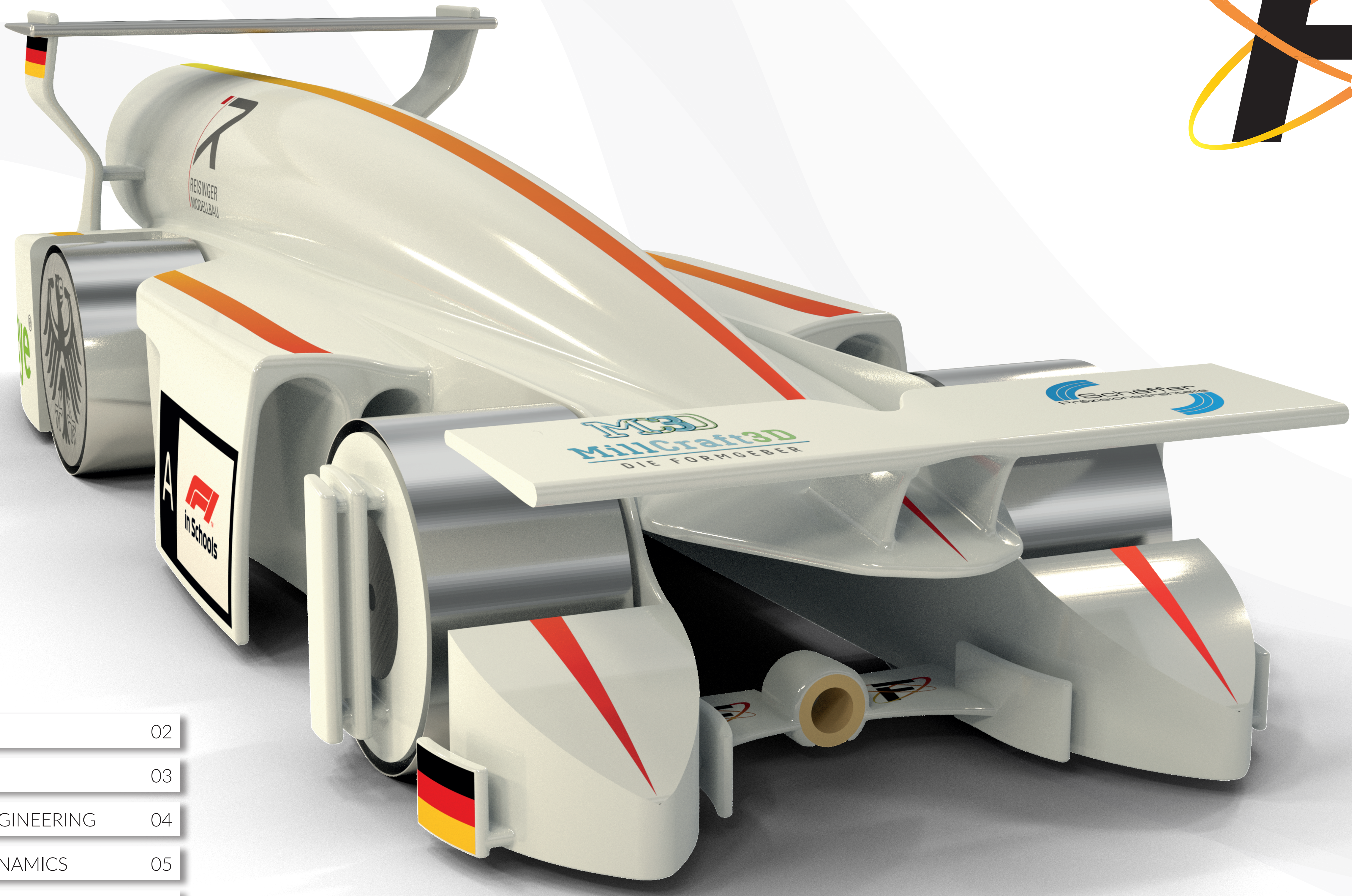
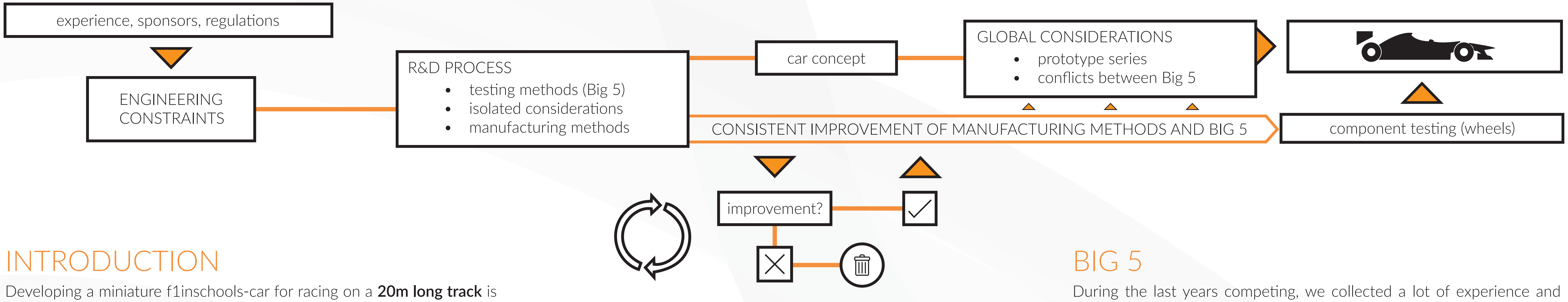

REISINGER
MODELLBAU
F1 in Schools
MillCraft3D
DIE FORMGEBER

GENERAL OVERVIEW



INTRODUCTION

Developing a miniature f1inschools-car for racing on a **20m long track** is a basic part of the competition. To earn the most possible points it is very important, that the car is constantly fast and complies with the f1wf19 technical regulations.
To improve track times it is essential to **reduce losses** caused by friction, aerodynamic drag etc. From an physical point of view all losses are caused by the Big5, which we will introduce later. To improve the race time isolated and global considerations are necessary.

Constraints

In the beginning of the development process, we had to **define constraints**. The most important part was to fulfill technical and competition rules. To set the financial and manufacturing constraints, we cooperated with our partners to get the best result possible. The exact analysis of the engineering constraints lays the **foundation for the research an development process**.

- Technical regulations + competition regulations
- Minimal car-mass (for optimal acceleration)
- Manufacturing constraints

CAR MASS

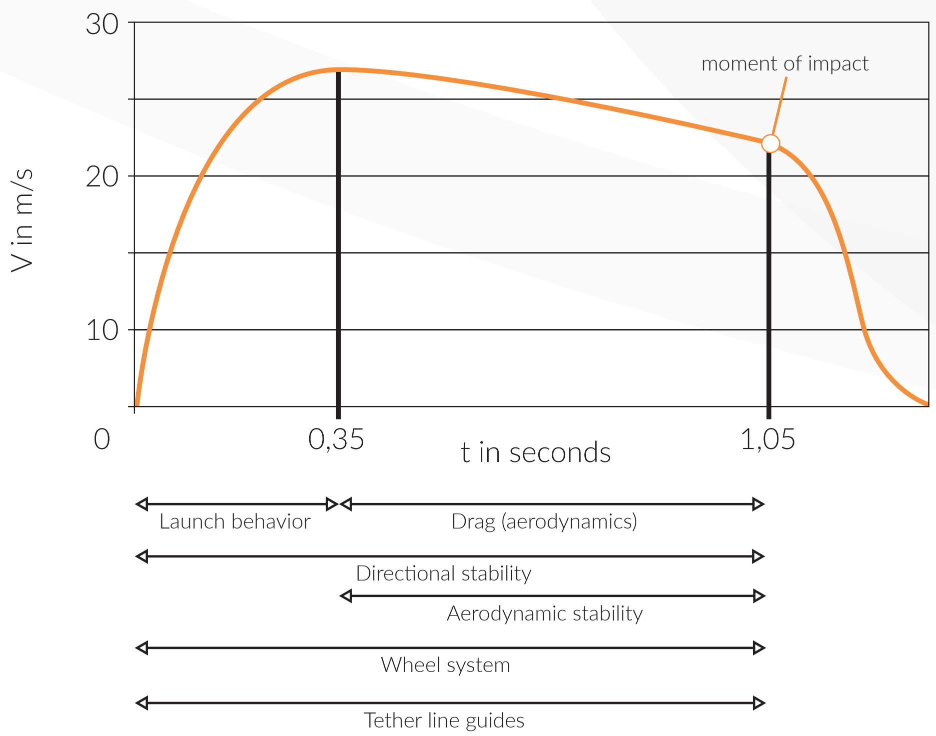
The equation for the cars launch is the following:

$E_{pot} = \frac{1}{2} * m_{car} * v^2$; it follows that: $v = \sqrt{\frac{2 * E_{pot}}{m_{car}}}$

As a result we decided to built a car with the minimal allowed mass. This helps to reach an higher speed. Track tests proved, that the minimal car mass is **practically more important than any other factor**.
While validating this theory, we found out that adding only 1g of weight increases the race time about 0,03 to 0,04 seconds.

SPEED CURVE

With the help of our innovative tracking system, we are able to **investigate the velocity** of the car. The race can be divided into two parts; the acceleration phase and the rolling phase. Each of Big5-factors influences specific race-periods; this is very important to understand before starting with isolated considerations.



BIG 5

During the last years competing, we collected a lot of experience and found out about the **fundamental aspects** that affect the race time. We call these aspects the "Big5". First of all, we go ahead with an isolated physical consideration. In the next step, we keep an eye on the relationship between the "Big5".

"Aerodynamic" drag describes the force that appeals to our car caused by the air on the race track.

"Launch behavior" summarizes hpw efficient the car uses the energy of the gas canister.

The "wheel system" includes everything from wheels or bearings to the axle system.

Another important aspect is the "Tether line guide," which can cause safety problems and friction.

"Driving behavior" (directional behavior) outlines how stable the car runs after being accelerated at the race-start.

VERIFIED ICON

We use this icon to show that **results given are based on tests**. Due to lack of space in this document we are not able to present data of the validation tests.

TESTING METHODS

For isolated and also global considerations, **tests are indispensable**. Therefore we developed numerous methods. In addition to that, we use these real-tests to validate computer-simulation (CFD/FEM) results.

TRACK TESTING

To test the exact impact of a changed factor on the track time, we use track tests. In addition to that, we developed and built a system consisting of **30 light-barriers** located on the race-track to measure the change of velocity.
We studied the **basics of experimental statistics** to improve the significance of the track test:

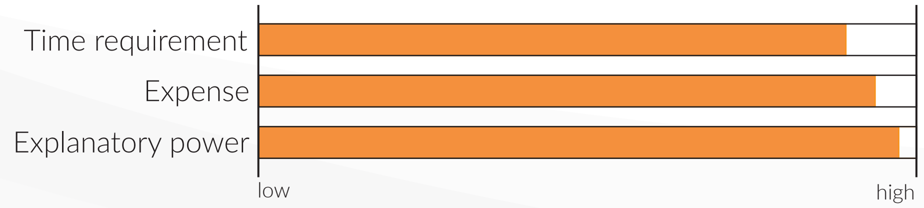
- While taking multiple measurements, the **values cluster** around the actual value, the main reasons for these **random errors** are environmental factors, like thermodynamic processes, and minimal variations in procedure.

➡ By rerunning the tests multiple times and deleting statistical outliers, we can minimize the impact of random errors. We decided to repeat the trial runs until the standard deviation reaches a value smaller than 0,015s.

- Systematic error is a steady, repeatable error associated with inaccurate equipment or flawed experimental design. This type of error can occur because of wrong calibrated or used measuring instruments.

➡ We are only testing to get relative, not absolute values; that's why systematical errors are almost irrelevant.

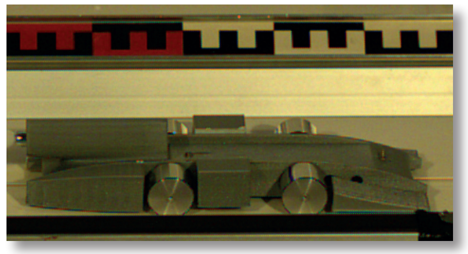
Evaluation



HIGHSPEED-VIDEO RECORDINGS

With the help of slow-motion recordings, we can **analyze** the launch behavior as well as the driving behavior of the car from different angles. To get decent results, the **highest possible framerate**, a well-lit racetrack, and a high resolution are essential. With the help of our sponsor, the „Youth Research Center Nagold", we have the opportunity to conduct these tests with a highspeed-camera, which can take up to 1.000.000 pictures per second. To save storage and to find the best possible compromise between framerate and resolution, we film with 5.000 fps. The results are viewed in a program called Phantom Cine Viewer; there, the video scene can be analyzed ideally.

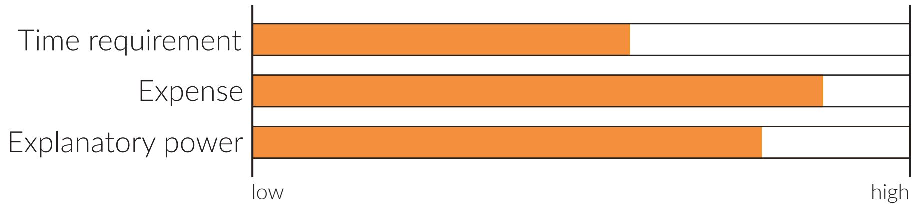
Launch behavior quotient



As explained in "Big 5", a better starting car doesn't rotate as much as a less efficient launching car. Caused by this rotation, the rear wheels lift from the ground and don't get accelerated anymore. It follows that the rotation speed of the rear wheels differs.

We use this to **quantify the launch behavior** with this quotient: $c_{lb} = \frac{n_{rear}}{n_{front}}$

Evaluation

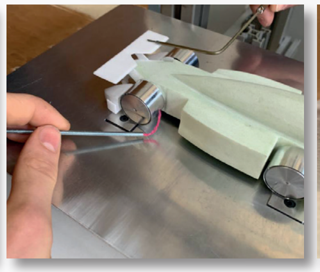
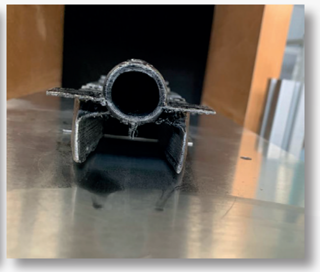


Note - repeating runs increases the explanatory power and time requirement.

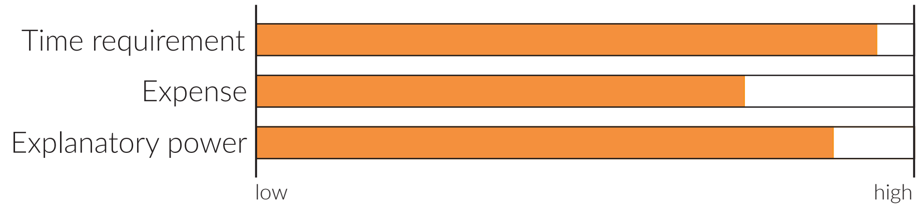
LABORATORY WIND TUNNEL

To measure the drag force appealing to the car, we use a test set-up with a **force sensor** applied to each wheel of the vehicle. For testing in the wind tunnel its necessary to produce a complete prototype with a smooth finish, because a rough surface could decrease the explanatory power. In addition to that, we develop our prototypes in the CFD-software with a smooth surface. It is very time-consuming to manufacture these prototypes, that is the reason why we use the measurements **only to validate** our **CFD-results**. Although **visualization** of the airflow is challenging, we found multiple methods that give us useful results:

- Smoke: the particles shows how the airflow interacts with the geometry
- Tufts: small string can show the direction of the airflow at a certain area
- Oil: By applying the fluid we are able to separate surfaces exposed to high friction from areas where slower airflow causes less friction.
- Hear-probe: With the help of this tool we can locate low-pressure areas.

Evaluation



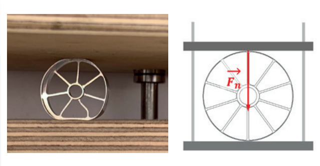
COMPONENT TESTING

Stress tests

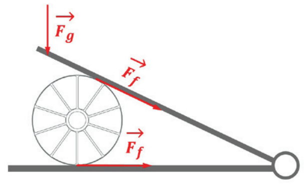
It is crucial for scoring maximum points on the race track that the car doesn't get damaged while deaccelerating. Speaking from experience of the last competitions, we can say that the **wings are the most fragile structure** of the geometry. To lower the risk of mechanical damage during the race, we conducted a stress test with a higher impact than usual. For this, we heated the gas-canister to increased the velocity of the car. However, this method is very cost-intensive; to minimize this, we calculated the wall-thickness and made **FEM-analysis**. In addition to that, we calculated if a mechanical failure occurs at a particular wall thickness. Therefore we used the **shear stress hypothesis**.

Component pre-selection testing

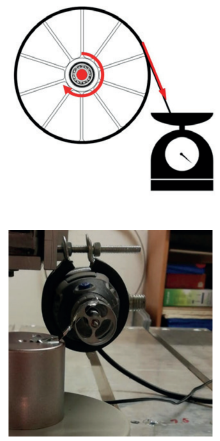
It is too time-consuming to determine the final components (materials, etc.) by track testing a **large number of variations**. Therefore we conduct isolated component tests to reduce the number of versions; the **suitable** ones **will be tested on track**. We developed the following experimental setups (the suitable components are shown in "final car setup"):



Wheels impact load



Wheels rolling surface friction



Bearing friction

Tether line guide friction

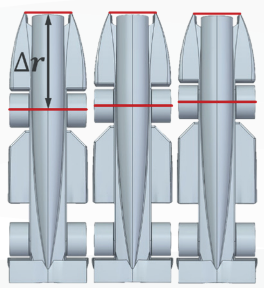
COMPUTER-AIDED-ENGINEERING

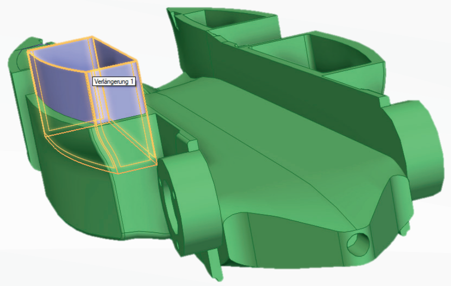
CAD includes the construction of a race car with all the necessary parts with a Computer-Aided-Software. We use a particular program, "Solid Edge 2019".

SOLID EDGE 2019

Parametric modelling

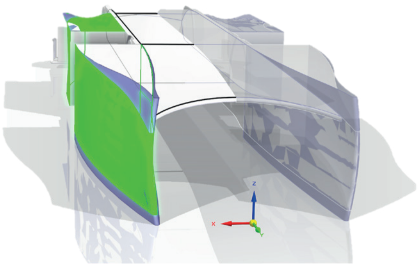
To ensure a time-efficient development process, **parametric modeling** is crucial. By this, we were able to run as many development-loops (CFD-simulations) as possible in a short period. We used an **EXCEL-table** to have a perfect overview of all the **variables** used in the model. After analyzing the results of a test, we can quickly generate new geometry by changing only the value of the variable. In addition to that, we can add **constraints and regulations**.

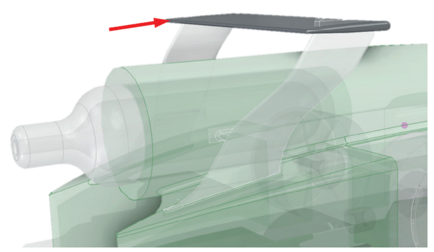




Hybrid construction

A hybrid construction, consisting of freeform-surfaces and ruled geometry, is the perfect option for a high-quality result. It allows very complex geometries, while having a low-computing time after making changes.





Freeform-surfacing

Due to free-form surfacing, we are able to model **almost any shape**. By combining two-dimensional curves to generate three-dimensional **cross-curves**, we can define the construction as **parametric**. For example, designing the side-pod, we used this modeling-technique.

Ruled geometry

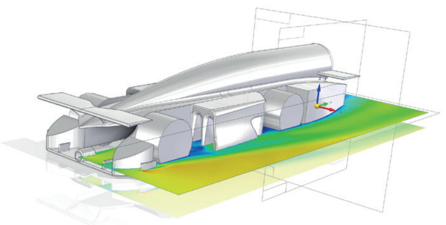
Ruled geometry is the perfect option for designing stable and simple shapes. **Two-dimensional sketches** define three-dimensional **solid bodies**. For example, creating the rear-wing, we used ruled geometry.

Designing tools

To improve our engineering-workflow and time-effectiveness, we use multiple tools.

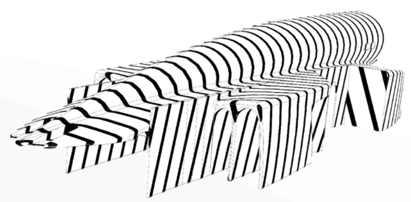
Visualization

By importing CFD-results into the CAD-data, we can improve the optimization of the geometry. We can make more accurate changes, and we can get a better understanding of the airflow.



Quality assurance (zebra stripes)

For controlling the surface of the geometry, we use tools like zebra-stripes. This helps us to detect uneven surfaces and construction-errors before CFD-simulations or the manufacturing process.



Goal seek (mass calculation)

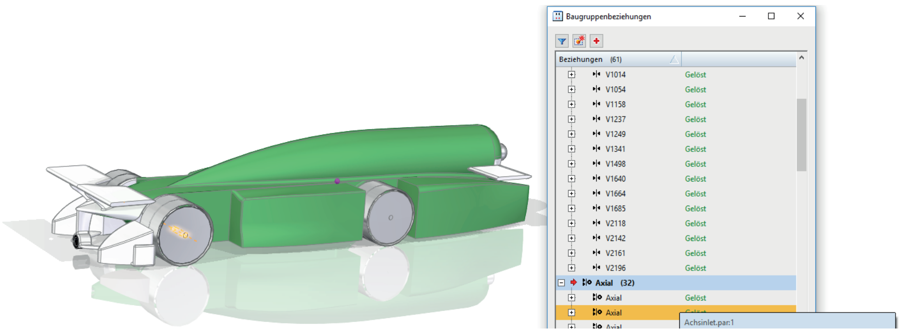
It is essential to calculate the **mass of the car** before coating to prevent the car from being overweight. In addition to that, we have the opportunity to **calculate the center of mass** (COM), this is also important to inhibit the car from tipping.

Target value

Primarily for prototypes, we used the feature called "target value", we give the target value and which parameter is variable. For example, the mass of a component should be 2g; to achieve this, we chose the wall-thickness as a variable parameter.

Solid Edge-Assembly

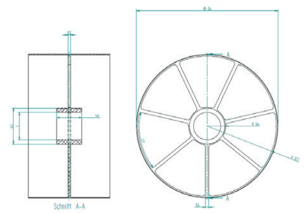
We use **peer-variables** to define fundamental values affecting multiple parts, e.g., overall-width or track-clearance. This ensures that the assembly is parametric. We also use **inter-part relations** to make changes more frugal.



Data output

To export data from Solid Edge, we tested multiple options; the following came up with the best results:

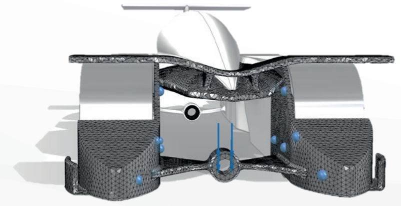
- Milling data (chassis): .step; .x_t; .x_b
- Turning parts: Technical Drawings Solid Edge .dft
- Renderings: .stl (very high resolution)
- CFD (Ansys Fluent/CFX): .sat
- Rapid Prototyping Components: .stl

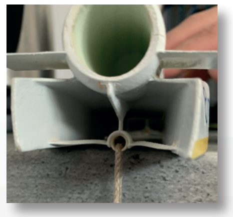


Note: Manufacturing constraints for simple manufacturing (wall thickness etc.) see "manufacturing".

FEM

For safety reasons, the tether-line guides have to be very stable. To prevent the structure from breaking, we conducted FEM-simulations and validated the results with real tests.





In addition to that, we tested the consequences of the car's **impact** after the race. Based on experience, we know that the **front-wing** is the most vulnerable component for a fracture. The force acting on the car, while slowing down from 23 m/s, is calculated as follows:

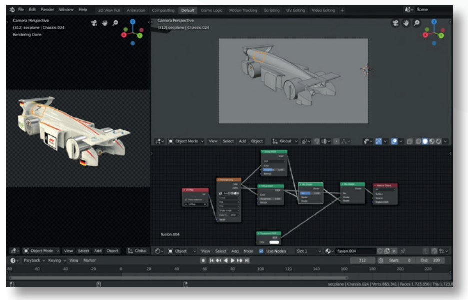
$F = m_{tot} * a$, with $m_{tot} = m_{car} + m_{empty\ canister} = 75,5g$

$$a = \frac{v^2 - v_0^{\,2}}{2 * s_b} = \frac{529\frac{m^2}{s^2} - 0\frac{m^2}{s^2}}{0,4\,m}$$ with the braking distance $s_b = 0,2m$

$$a = 1322,5\frac{m}{s^2};\ F = 1322,5\frac{m}{s^2} * 0,0755\,kg = 99,84\,N \approx 100N...$$

Renderings (Blender)

To present the car and other components professionally, we create renderings. We chose Blender because it gives us many opportunities to create a **custom set-up**. In addition to that, we are able to make high-quality animations.



COMPUTER-FLUID-DYNAMICS

Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical analysis and data structures to analyze and solve problems that involve **fluid flows**, which in our case is a race car on the racetrack. We use CFD-Simulations besides a real wind tunnel, which would have given as more nearly as accurate results but would have had many problems e.g., the need to build the car for every different test or the lack of visual analysis. Following by that we decided to use the CFD-Simulations while validating them with the wind tunnel and real racetrack tests. To use the CFD-Simulations, we constructed different solutions for our aerodynamic problems and then solved them. With the results, we were able to improve the aerodynamics of our car.

COMPARING OF SOFTWARE

Autodesk Flow Design

+ very user-friendly
+ short processing time
− inaccurate results
− few modifiable parameters

FLOW

OpenFOAM (+Paraview)

+ user-friendly
• acceptable processing time (additional handling time)
• acceptable results
− few modifiable parameters

OpenFOAM

Ansys Fluent

• acceptable processing time
• (additional handling time)
+ many modifiable parameters
+ very accurate results
+ many modifiable parameters (+turning wheels and moving race-track)
+ many options to visualize results

ANSYS Fluent

Ansys CFX

+ accurate results
+ most advantages of ANSYS Fluent
+ accurate results
+ more time-efficient than ANSYS Fluent

ANSYS CFX®

We decided to use ANSYS CFX to test different concepts and ANSYS Fluent to conduct more specific comparisons. This helped us to get the best possible results in the shortest period.

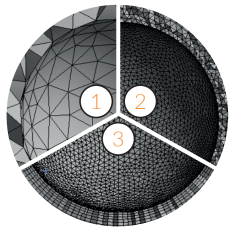
The most important steps during the simulation are:

1. Exporting the SolidEdge .par-file as **.sat-file**.
2. Using ANSYS Workbench, which is the base-software for all ANSYS programs, we start our CFD workflow.
3. Steps in the ANSYS Modeler:

- the wind tunnel boundaries and racetrack get set
- Adding a **Body of Influence** (BOI) for even more accurate results

4. Creating the mesh (network formed of cells and points)

- the elements can have any shape in any size
- each cell of the mesh represents an individual solution of the equation, which combined, results in the simulation
- the mesh is formed out of 20-35 million elements, shaped tetrahedral
- forming of an inflation to get even more accurate results



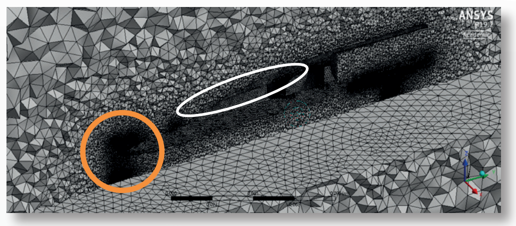
1 - big theadral elements
2 - fine theadral elements
3 - theadral and pentagonal elements

5. Creating a setup with multiple boundaries like the pressure-outlet, racetracks and car. We used three different models (k-epsilon, k-omega and k-omega sst), the **k-omega sst** model worked in the most cases.
6. Simulation of the model (~ 7 hours).
7. Report of results and analysis:

- drag force (coefficient) and center of pressure
- visualization with isosurfaces, surface pressure, vector arrows and streamlines

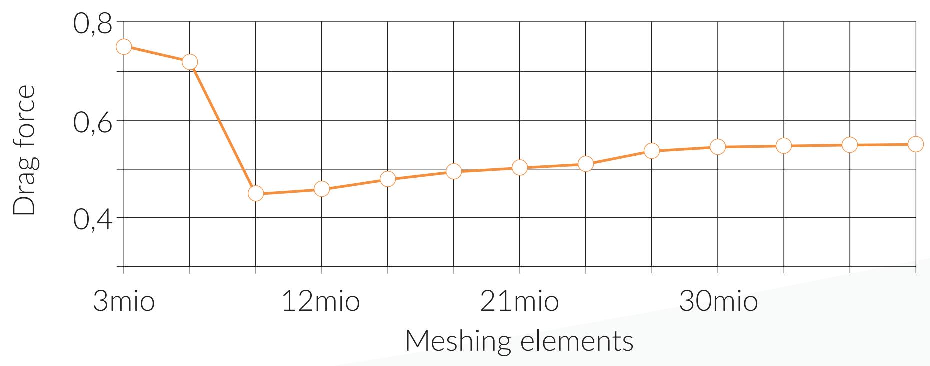
Mesh resolution

As shown in the picture below, the **element size of the mesh varies** between the **areas of the car**. We found out that, for example, the airflow around the front-blocks has a massive influence on the rest of the flow. Due to that, we increase the resolution in this area, to analyze the airflow better, because the smallest changes can have an enormous impact. Contrary to that the investigating the airflow at the canister-chamber doesn't require that precise numbers; to improve efficiency, we simulated fewer elements.



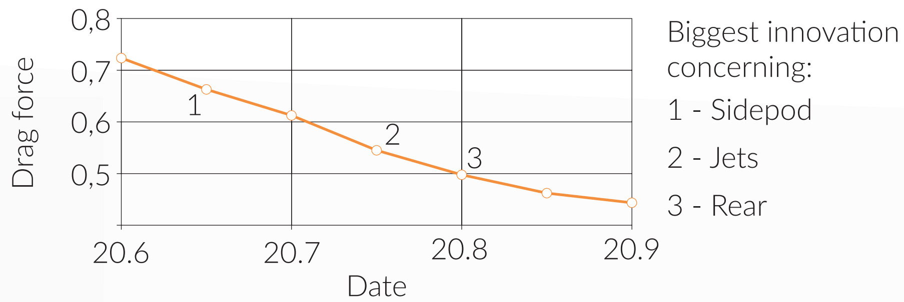
MESH CONVERGENCE STUDY

In CFD-analysis, a finer mesh typically results in a more accurate solution. However, as a mesh is made finer, the processing time increases. To get the perfect **balance between the quality of the results and processing time**, we conducted a mesh convergence study. The best balance between quality and solving time is found when the mesh has **35 million elements** on this point; the results nearly don't change anymore.



THE DIRECTION OF OPTIMIZATION

For the German Nationals, we developed our car from the front to the rear. By doing this, we could ensure not to override any optimizations made before. After receiving the **new regulations** for the World Finals, we directly started to test the areas with the most improvement potential. After that, we continued to develop from the front to the rear end, but this time we ensured to focus on the marked red areas. By that, we were able to make faster progress than ever before. For evaluating the **improvement potential** of a specific area, we also studied former simulation-results; then we analyzed the **impact on the drag-force** by changing the geometry very little.



RESEARCH & DEVELOPMENT

At the beginning of the research and development process, we started with **isolated considerations** of the Big5. Thereby it is possible to create an open car concept, which lays the foundation for testing with prototype series (global considerations). In addition to that, we can fix parameters for different components like wheels or tether-line-guides.

AERODYNAMIC DRAG

Drag gets defined as the force being generated by a solid object, moving a fluid. Because this force is pointing in the opposite of driving direction slowing down the car, reducing it improves our track-time.

The general equation to calculate drag: $F_W = \frac{1}{2} * A * c_w * \rho_{Air} * v^2$

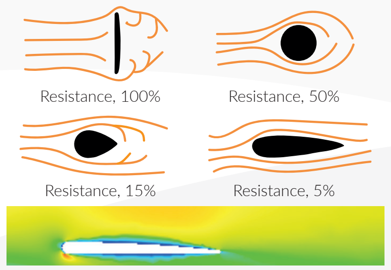
The only factors to be minimized are:

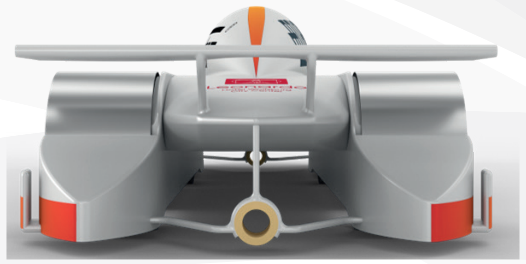
: cross sectional area of the car & c_w : drag coefficent

It follows that the cross-sectional area and the drag coefficient of the car have to be reduced to achieve an aerodynamic car.

To accelerate our aerodynamic-development process, we searched for different concepts to adapt:

- The **drop shape** suits perfectly for the car's wings and other struts like the connection of the tether-line guides.
- Another adaption is the **rocket-shape** of the canister-chamber. By splitting the air up consistently, we can decrease more significant pressure differences, especially behind the car.
- We use **jets** and turning vanes to manipulate the airflow positively, adapted from an aero-prototype from Mercedes.
- To minimize the area exposed to the airflow, we got inspired by the **catamaran concept**.





Conclusion

To minimize the drag of the car, it must comply with the following parameters:

- small cross-sectional surface + low drag coefficient

➡ reducing the force by development with aerodynamic testing methods

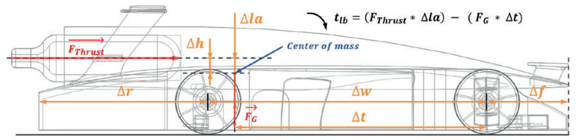
- long car (with a short wheelbase) and minimal dimensions for wheels and gas-canister chamber

➡ reducing the angle of the faces on the chassis

➡ keeping the cross-sections surface small

LAUNCH BEHAVIOUR

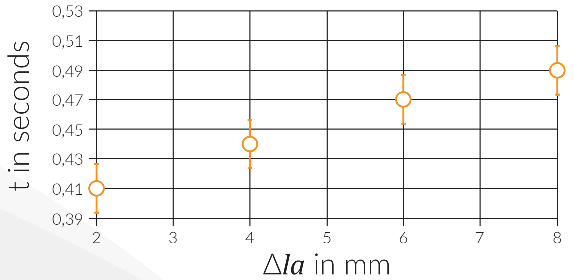
Trough analyzing slow-motion videos, we found out that the rear of the regional finals car is lifting at the beginning of the race. The reason for this torque can be explained as follows:



To use most of the thrust-force for acceleration in driving direction, the rotation shown in the drawing has to be minimized. To reduce t_{lb} (without minimizing the thrust or maximizing the cars weight), the car must comply with the following parameters:

- Δt has to be maximized, (while Δf and Δr have to be minimized)
- Δla has to be reduced
- the wheelbase Δw has to be as long as possible to prevent the car from tipping at rest (com has to be front of the rear axle)
- following by that Δh has to be reduced

To prove this theory, we used a prototype and measured the following results:



Result

If Δla decreases, more energy can be used for horizontal acceleration

➡ **Δla has to minimized**

Additionally we were able to proof the theory for their horizontal position with another test-series.

To improve the position of the com we researched for different solutions:

- By using **lightweight**-design structures in the **underbody**, we are able to save weight for distributing it higher in the car.
- To **re-distribute mass higher** in the rear, we consider using **metal** for the rear wing.

TETHER LINE GUIDES

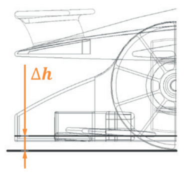
The movement of the car causes a sliding friction occurs at the points of contact between the cord and tether line guides. **Sliding friction** can be calculated as follows: $F_s = \mu_s * F_n$

Three forces are causing the friction between the nylon cord and the tether line guide:

F_1 is the force that is needed to accelerate the chord in a vertical direction

F_2 is the force that is caused by lateral deviating.

F_3 is the gravitational force of the nylon cord.



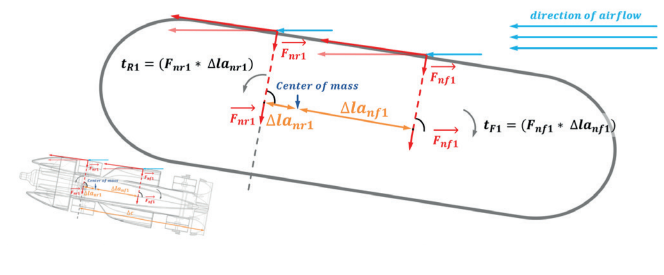
Simplified, we came to the result that the cars tether line guides need to comply with the following parameters to minimize losses:

- Δh has to be minimized
- sliding friction coefficient μ_s has to be reduced

The horizontal positions of the tether line guides from side view will be discussed in "directional stability".

DIRECTIONAL STABILITIY

With the help of slow-motion videos, we are able to observe the behavior of the car during the race. As a result, we found out that some prototypes **turn** their **nose to the side** during the race. The torque causing this behavior occurs because of various factors, e.g., minimal friction differences at the wheel-system. It is necessary for minimizing losses to design a car that does not increase this behavior due to its geometry (aerodynamics); a "**dynamical stable system**" is the aspired goal. To reach this, we made the following analysis:



To improve the **aerodynamic stability** (position of the center of pressure) the car has to comply with the following parameters:

$T_{r;tot} > T_{f;tot}$

- with $T_{r;tot}$ summarizing all the torques rear of the COM
- with $T_{f;tot}$ summarizing all the torques front of the COM

To improve the optimization process and **quantify** the aerodynamic stability of prototypes, we developed a method featuring **CFD-simulations**. We simulate the geometry with an 10° angle and read out the three force components applying to the most critical vertical faces of the car. With that information we can **calculate the torque generated by the force**. To summarize the aerodynamic stability of a car, we use this quotient: $c_{as} = \frac{T_{r;tot}}{T_{f;tot}}$

A **concept** to improve the aerodynamic stability is to adapt the **fletchings of an arrow**. These fletchings add vertical faces behind the arrows com to add stability while moving. Components like the rear wing can add faces like the fins of an arrow.

RESEARCH & DEVELOPMENT

In addition to this, the wheelbase (which implicates the horizontal position of the **tether line guides**) has to be maximized to improve the directional stability. A high distance between these components **extends the lever-arms** of the counter-torques, leading to an **smaller deviation angle**.

To maximize the directional stability, the car must comply with the following parameters:

- increased vertical faces rear of the COM
- decreased vertical faces in front of the COM has to be minimized (position of COM)
- the distance between wheels and TLGs has to be maximized

WHEELS & WHEELSYSTEM

The rotation of the wheels the cars allows the car to move forward; hence, it is essential to reduce losses.

Mass moment of inertia

Because the energy stored as rotational energy can`t be used for movement, the moment of inertia has to be reduced as much as possible.

The rotational energy is being calculated as follows: $E_{Rot} = \frac{1}{2} * J_{tot} * \omega^2$

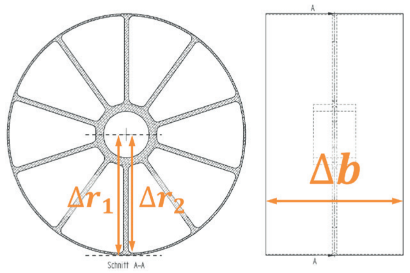
The volume of the wheels can be simplified as a hollow cylinder. As a result of the calculations we got: $J_{rum} + J_{hub} << J_{rolling\ surface}$

➡ **optimization of the rolling surface** takes top priority

Approximated calculation for the moment of inertia

$$J_{wheel} = m * \left(\frac{r_1^2 + r_2^2}{2}\right) = \rho_{wheel} * V_{wheel} * \left(\frac{r_1^2 + r_2^2}{2}\right) = \rho_{wheel} * b * \pi * (r_2^2 - r_1^2) * \left(\frac{r_1^2 + r_2^2}{2}\right)$$

$$= \frac{1}{2} * \rho_{wheel} * \pi * b * (r_1^4 - r_2^4)$$



To minimize the rotational energy, the wheels must comply with the following parameters:

- as to be minimized (allowed min.: $b = 15mm$)
- the radius r_1 has to be minimized (allowed min.: $r_1 = 13mm$)

the rolling surface thickness has to be reduced as much as possible, the **density** of the wheel ρ is of **secondary importance**, because:

$$J_{Wheel} \sim \rho_{Wheel} * (r_1^4 - r_2^4)$$

Track-tests needed to determine the perfect material and wall thickness of the rolling surface.

Bearings (Friction)

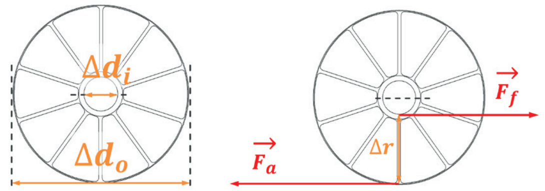
The friction caused by the rotating wheels can be calculated as follows:

$F_f = \mu_{roll} * F_N$; as follows F_f can be reduced if:

F_N is minimal (car weight constraint)

μ_{roll} is minimal (dependent on the materials assembled)

➡ Test are needed to find a low-friction-bearing **material combination**.

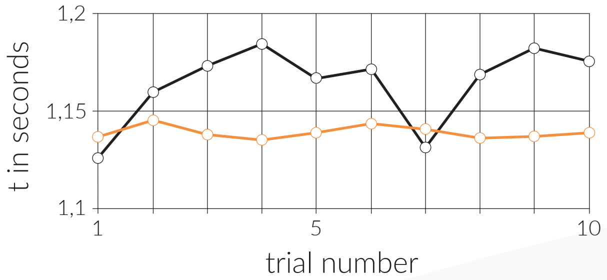


The force needed to overcome the friction force F_f at the start is being calculated like this: $F_a = \frac{F_f}{r^2}$, with $r = \frac{1}{2} * (d_o - d_i)$. To minimize F_a:

- d_i (diameter of the bearing) has to be minimized
- the cars weight has to be minimized (weight constraint)
- the wheel diameter d_o has to be maximized (error: rotational energy)

Bearings (Number)

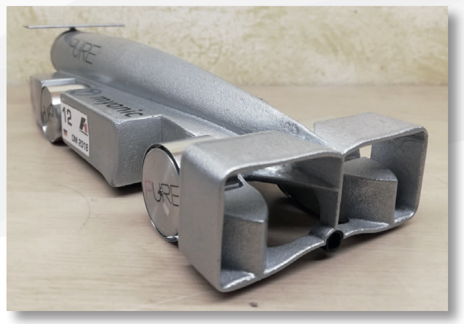
Using two bearings per wheel adds more **stability** to the wheel and improves the directional stability. On the other hand, it increases the **momentum of inertia**. To find the perfect compromise, we tested both versions on track:



Result
Assembling the wheels with two bearings per wheel makes the car faster and more constant. So we chose to use 2 bearings.

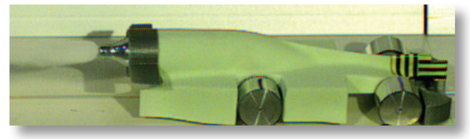
CAR CONCEPT – "FOUNDATIONS"

By **putting all the isolated considerations together**, we came up with a catamaran-like car concept. However, many of the dimensions and **parameters** of the concept **have to get defined**. In preparation for the national finals, we tested some, so-called "basic foundations," which need to be set before global considerations:



Car length

The theory that the most extensive possible length is the best was proven by testing shorter prototypes. The longer car has better directional stability and aerodynamics while weighing more than shorter ones (mass can be distributed better; for launch behavior)



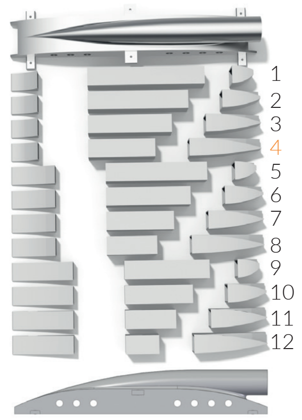
Minimal width dimensions

(considering wheels): To decrease the cross-sectional surface and gain an **aerodynamic advantage**, we tested that a car with small width dimensions can compensate for the slight disadvantage, of being less directional stable, easily.

Approximately wheel locations

To find the perfect **wheel positions approximately**, we built a prototype, which has modifiable locations of the axles and additional components:

1,194 - 1
1,178 - 2
1,167 - 3
1,177 - 4
1,177 - 5
1,170 - 6
1,167 - 7
1,180 - 8
1,172 - 9
1,180 - 10
1,197 - 11
1,210 - 12



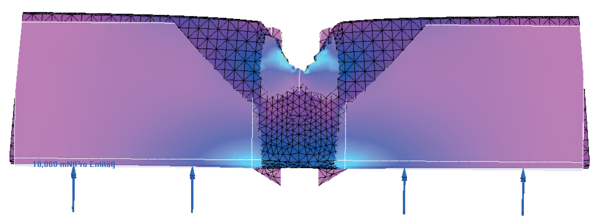
Conclusion

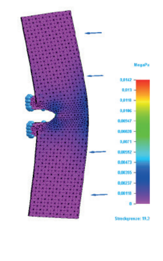
- the **front** of the car has to be as **short as possible**
- the **rear-length** cant be defined because of to **small deviations**

➡ new test series with complete and more accurate prototypes needed.

Upward-moved-front wing geometry

Part of the catamaran car-concept is the **upward moved front wing**; this free-standing geometry increases the risk of a fraction. Therefore we examine the effect of the breaking-impact on the front geometry. The perfect compromise between stability, aerodynamic stability, and drag is the double-brace. Due to this, we increased the **freedom of form for the front-block** massively.



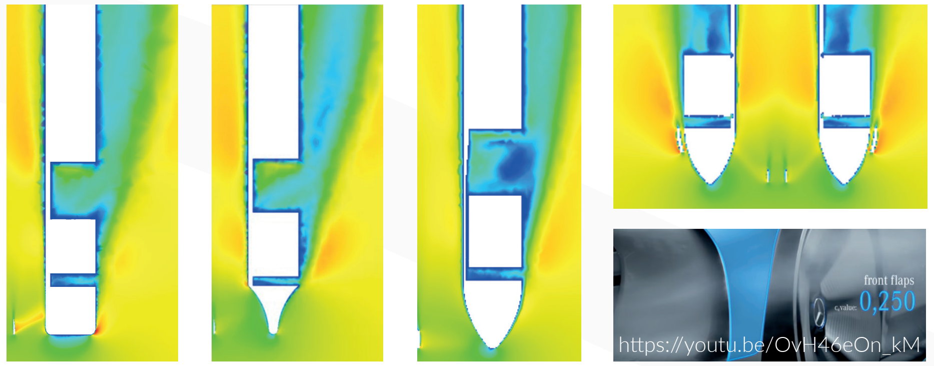


DESIGN PROCESS

INNOVATIVE DESIGN PROCESS

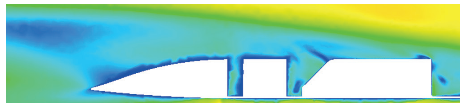
Designing a new geometry based on the car concept requires a high-end CFD-software and multiple **innovative design-features**. Therefore we looked for ideas in **industry**, **nature**, etc. However, we are not able to show more than two concepts in detail, due to lack of space. The ones with the **most significant benefit** are **volume distribution**, **drop-shape**, **rocket-shape**, **turning vanes**, and **jets**.

Front block (sideways airflow)

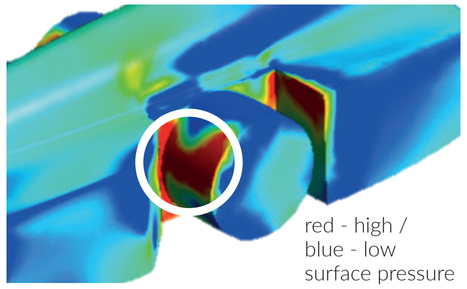


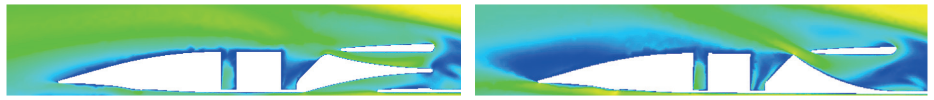
The convex front-block showed the best potential. To prevent the airflow from demolishing, we added **flaps** inspired by the **car industry**.

Sidepod / Underbody

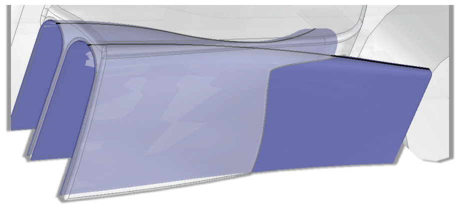


Because of the new exclusion-zone the airflow hits the wheel surface and causes vortexes behind the car. To prevent this we tested different concepts.



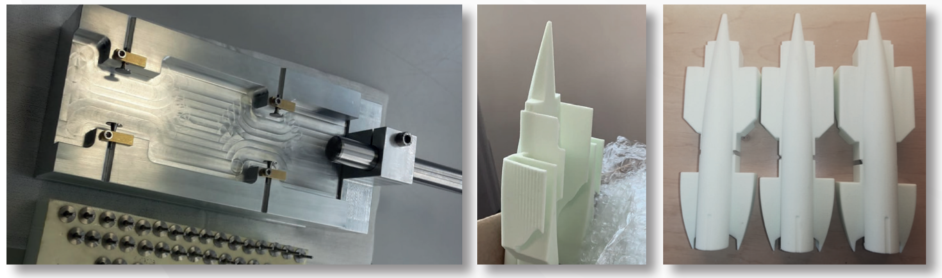


The geometry of the left picture unites the airflow behind the car very good, because more air streams through the cars middle-channel and accelerated air, flowing through the exclusion zone, **prevents vortexes**.

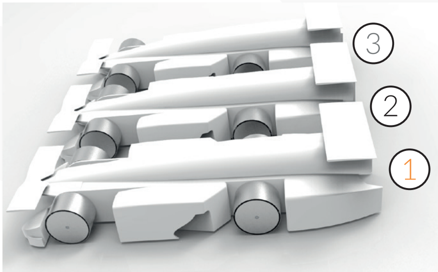


SERIES 1 - WHEELBASE

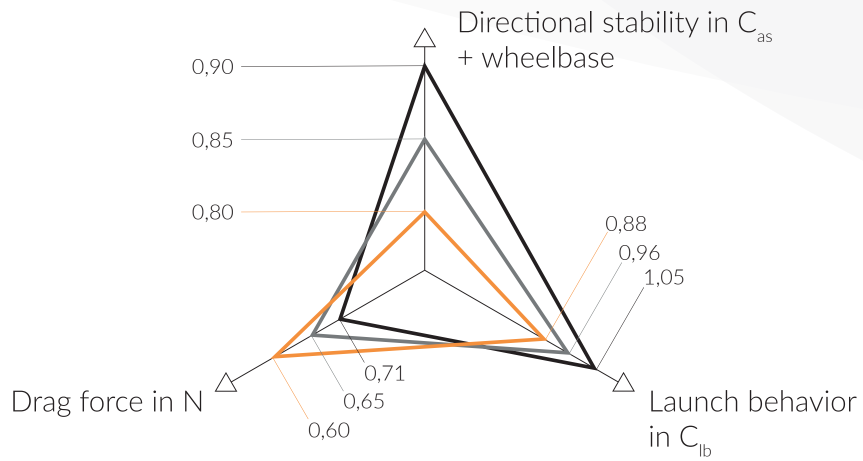
The **wheelbase** of the car has a high impact on aerodynamics, directional stability, and launch behavior. To improve manufacturing quality, we decided to develop a device for the **axle-system assembly**. The development and manufacturing are very time-consuming; as a result of that, we had to **determine the wheelbase very early**.



In addition to that, the first series helped us to push the boundaries of the milling process. Our partner Reisinger Modellbau has never milled a geometry like this before; so we had to test if this was even possible.



	Average race time
CAR 1	1.109
CAR 2	1.124
CAR 3	1.176

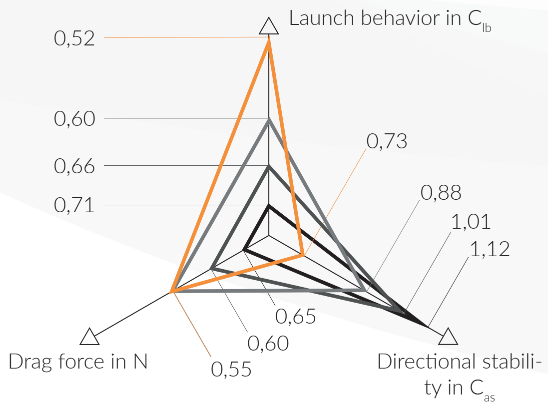


As a result, we found out that the rear should be as short as possible (for the tested wheelbases: 101mm; 105,5mm; 110mm). Because of that, we increased the **wheelbase** to **110mm**.

SERIES 2

After determining the wheelbase, we decided to test the **influence of aerodynamic stability** (an aspect of directional stability) on the car's track time. Therefore we built a prototype-series consisting of four test-cars. All these cars have the same wheel-system and tether line guide components; only the **main three competing factors differ** between the set-ups.

CAR 1		directional stability	launch efficiency	drag
Heavy front	✓	↗	↘	→
Fin at the car	✓	↗	↘	↘
Lightweight rearwing	✓	↗	↘	→
CAR 2				
Heavy front	✓	↗	↘	→
Fin at the car	✗	↘	↗	↗
Lightweight rearwing	✓	↗	↘	→
CAR 3				
Heavy front	✗	↘	↗	→
Fin at the car	✗	↘	↗	↗
Lightweight rearwing	✗	↘	↗	→
Weight balance: rear		↘	↗	→
CAR 4				
Heavy front	✗	↘	↗	→
Fin at the car	✗	↘	↗	↗
Lightweight rearwing	✗	↘	↗	→
Weight balance: rear		→	→	→

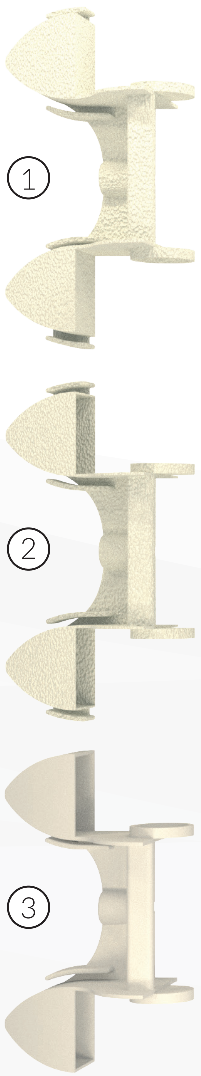


	Average race time
CAR 1	1.108
CAR 2	1.099
CAR 3	1.076
CAR 4	1.074

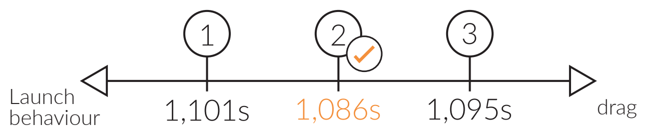
From the analysis above, we know that **aerodynamic stability is not as important as launch-behavior and drag**. We found out that these two are the most critical competing factors, but it is not possible to say exactly which one is more important. Therefore we tested the **final chassis with different set-ups**.

FINAL CAR-SETUP

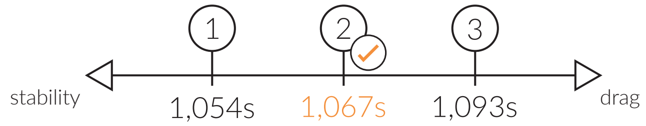
General information
To achieve the best **set-up** of the final chassis, we tested different nose-cone geometries and other **additional car-parts** influencing the three competing Big5´s. The components with different geometry influence the drag/launch-behavior balance. In addition to that, we examined the **durability** of the rear wing structure, because adding more weight due to denser material increases the danger of material failure. In the second car-setup testing, we tested multiple **additional components** like **wheels** or **tether-line guides**, to find the fastest option.

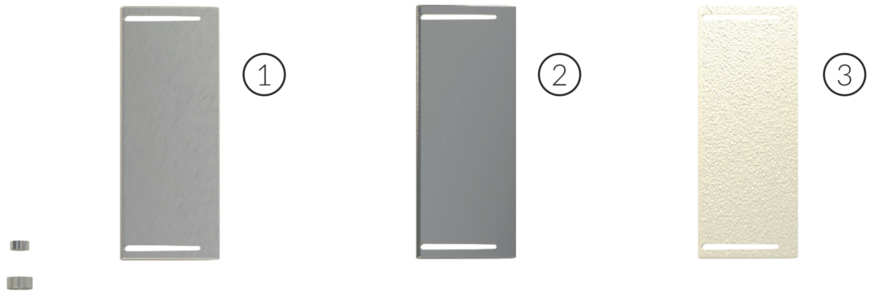


front
Adding turning vanes to the nose-geometry helps to optimize the airflow and reduce **drag**. On the other hand, the **launch-efficiency** gets worse by adding mass directly above the track surface at the front end of the car.

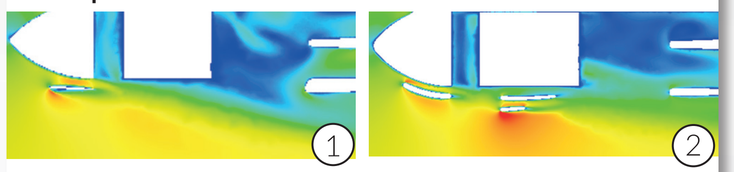


rearwing
The heavier the rear wing, the better the **launch behavior**. To prevent the rear wing-structure from breaking the mass has to be as little as possible. To find the perfect compromise, we are testing on track. Racing with a steel wing is the fastest option, but using the aluminium structure lowers the **risk of material failure**.

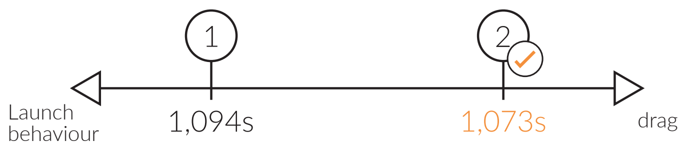




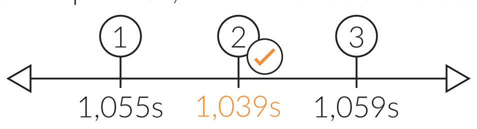
hubcap



The **added** jet on the outside of the wheel improves the efficiency of the outer channel of the side-pod. By **manipulating the airflow early**, we can prevent stalls. On the other hand, the added component shifts the center of mass and **decreases launch-efficiency**.



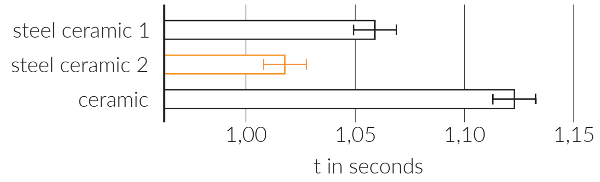
rearwing support structure
We found out that the rearwing support-structure can have a positive impact on the launch behavior. By shaping the side-structures, it is possible to **compress the airflow around the gas-canister chamber** and make the launch more efficient. On the other hand, this **increases drag-force**; to find the perfect compromise, we conduct track-tests.



wheels
Reducing the **number of spokes** of the wheel rim lowers the **moment of inertia**, in addition to that the **durability** gets diminished. The car's components have to last multiple races; to find the perfect compromise, we conduct track tests with up to 10 iterations.

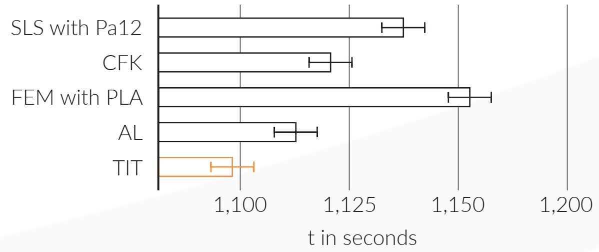
COMPONENT TESTS

Bearings
It is possible to pre-select bearings for the car, but isolated test do give only too inaccurate results to choose the final component.



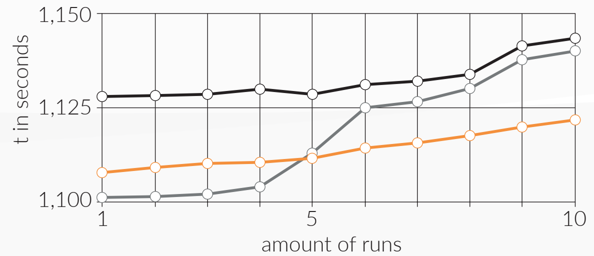
Results
For the final car we use myonic-hybrid bearing consisting of steel and ceramic. The geometry is protected good against entering particles.

Wheels – material and manufacturing method
After preselecting wheels and materials, we can choose from a smaller amount of suitable options for the final-track testing loop:



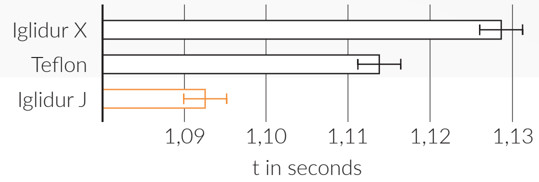
Results
The result is that titanal is the fastest and most durable option. To determine the perfect geometry, we conduct a durability-race time test (see the rendering).

Wheels – rolling-surface thickness
A thin rolling surface reduces the moment of inertia while being more vulnerable for damage. To find the perfect compromise, we test the track-time progress during the first ten races. Repeating this four times helps us to improve the explanatory power of the whole test scope.



Results
The result is that 0,08mm suits perfectly for the race-requirements. The thinner version 0,05mm is not durable enough.

Tether line guides
To find the material causing the least friction, we conduct track testing. In addition to that, we can include the impact of the materials-density on the launch behavior.



Results
We use Iglidur J tether-line guides because the combination of low-friction and lightweight-material show the best track-time.

MANUFACTURING

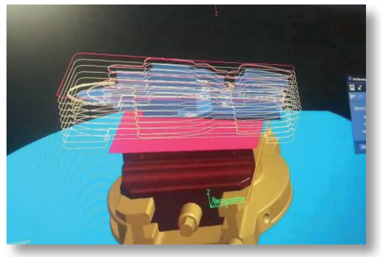
Manufacturing is what brings our idea to life. Without a good manufacturing we can't reach the theoretically possible race time. Therefore, it's vital to set **high manufacturing standards**.

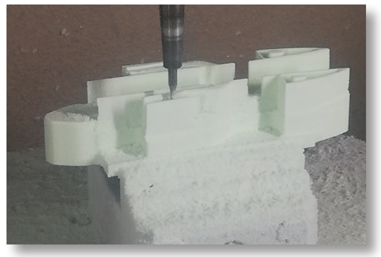
- maximum precision
- Optimal car weight of 50.5g
- maximum quality
- Safe workplace area

CAM

With the help of the CAM (computer-aided-manufacturing) software **tebis 4.6**, we created the machining code for our chassis and rear wing. The overall goal was to obtain a result with a flawless geometry and a smooth surface. Moreover, it was crucial for us to create an efficient CAM file to avoid a long and intensive machining time.
At some areas of the chassis, the wall thickness is only 1mm. This could lead to major problems during the milling process. For instance, a crack or ripples surface could occur. The final CAM file is formed with the help of an **iterative process** to find the optimal **balance between a perfect result** and **low machining time**. We started with a very low feed rate (180 mm/s) and increased it until problems occur (1000mm/s). Because of that, we are able to **decrease the machining time from 180 minutes to 70 minutes**.

1. In order to be able to mill the chassis, we decide to separate the milling process into **two strains**. In the first strain, we can chuck the chassis directly into the machine-vice. For the second strain, we first had to mill a jig out of hard plastic holding the chassis with a press-fit (lower tolerances).
2. Inserting a **STEP-file** of our chassis into tebis and tell the program the position of the model block relating to the zero point of the machine. The **zero point** sits on the worktable of the machine to avoid collisions.
3. Now tebis was basically able to calculate with the information about the availability of tools and the specifications of the mill the **optimal toolpath**. The toolpath had to be assigned manually in some difficult locations, e.g., the inner side of the sidepod.
4. Improve the areas with a low wall thickness as described.
5. Watching the simulations of all toolpaths to recognize possible mistakes, e.g. collisions and to improve the machine code.
6. In the last step, the post-processor calculates the CAM file to a **G-Code** for the machine.





CNC-MILLING

We milled our chassis with the "**Hermle C40u–dynamic**" because it is a **5-axis simultaneously** (all axis can move together) mill. So we were able to manufacture advanced non-planar surfaces. First, we had to transfer the created G-code to the mill. After that, we inserted the needed tools in the mill and secured the model block centred in the machine vice. We milled the chassis with 14000 rpm according to the following steps:

First strain

1. Milling the chassis with a toric end mill (d = 12mm r = 1mm), a feed rate of 12000mm/s, and a step of 7mm ➡ reduce machining time
2. Milling the planar surfaces with an endmill d = 6mm and a feed rate of 5600mm/s. For the 1mm thin sidewalls, we reduced the feed rate to 1000mm/s ➡ to avoid a fracture of this geometry
3. Milling of the rear sidepods with a toric endmill (d = 4mm r = 1mm) and a feed rate of 7500mm/s ➡ reduce machining time
4. Finishing the outer non-planar surfaces with a ball mill (r = 8mm) and a feed rate of 6600mm/s ➡ smooth surface finish
5. Finishing of the sidepods and the underbody with a ball mill (d = 4mm) and a feed rate of 4400mm/s. For the fracture-critical sidepods, we split the process into three steps with different feed rates (4400mm/s, 3000mm/s, 2500mm/s). The thinner the material, the smaller the feed rate ➡ avoiding fracture + lower machining time.

Second strain

1. Milling of the chassis-holding-jig out of hard plastic and secure the chassis (without opening the vice) with a press-fit ➡ for high accuracy, no steps between the two strains
2. Rough milling of the chassis with a toric end mill (d = 12 mm r = 1mm), a feed rate of 8500 mm/s, and only a step of 1mm ➡ a reduced step to avoid loosening the press-fit.
3. Pre-finishing of the outer surface of the cartridge chamber with a ball-mill (r = 4mm) and a feed rate of 6700 mm/s ➡ lower machining time and more accuracy for the chamber safety zone
4. Finishing of the chassis with a ball-mill (r = 2 mm) and a feed rate of 4500 mm/s by using the simultaneous functionality. ➡ Reduces the time to create the CAM-file.
5. Finishing of the radii with a ball-mill (r = 1mm) and a feed rate of 2200 mm/s by using the simultaneous functionality. ➡ Makes it possible to mill those areas.
6. Milling of the recesses for the 3D-printed parts with a ball-mill r = 0,5mm and a feed rate of 1000 mm/s ➡ accurate fit for the 3D-printed parts.

3D-PRINTING

To improve **our freedom of design** for additional components, we decided to rely on rapid prototyping. After investigating different methods, we came up with the following results:

	Fused Deposition Modeling with ABS	Polygraphy with VeroWhite	Stereolithography with Accura Xtreme	Selective laser sintering with PA12
breaking stress in MPa	33	50 - 65	38	66 - 73
layer thickness in mm	0.18 - 0.25	0.016 - 0.03	0.05 - 0.1	0.1 - 0.15
min. wall thickness in mm	0.8	0.5	0.4	0.3
Density in g/cm³	1.04	1.17 - 1.18	1.09	0.93 - 1.01
Precision in µm	~500	~300	~400	~400

➡ We chose the **SLS-manufacturing process** because it suits perfectly for our high requirements.

SLS (Selective laser sintering) is an additive manufacturing technique that uses a laser to sinter a preheated polyamide powder (polyamide 12) layer by layer. In each layer, a complete powder coat is added and merged to the already melted particles. Those layers are 0.1mm to 0.15mm thick, which results in a relatively rough surface area. A time-consuming sanding process can improve this finish quality tremendously.

Quality assurance

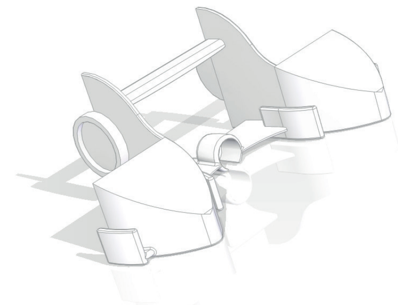
To optimize the properties and ensure the quality of the final part, we printed test geometries with different wall thicknesses. By evaluating those parts, we figured out that **0.3 mm is the lowest possible wall thickness**, which complies with our quality requirements.

Workplace safety

- wearing respirators, gloves and safety glasses while dusting the components off

Manufacturing Constraints

- minimum wall thickness 0.3 mm



MANUFACTURING

TURNING

For optimal directional stability and minimal friction, we have **very high requirements concerning precision and strength** of the axle geometry. In comparison to other manufacturing techniques, like rapid prototyping, turning is very precise. When it comes to the manufacturing of round parts, the accuracy is even higher than milling. For our geometries, we used the **Spinner Tc 32 Mc**, a lathe with six-axis of freedom and high precision. To meet our high manufacturing goals, we **validate** our manufacturing results with the **SPC-method**. We manufactured all turning parts according to the following steps:

1. technical drawing
2. determine the coordinates
3. compiling the program
4. applying tools and materials
5. set up the bar loader
6. test running of the program
7. improve the program

normal distribution				
classes	distribution	number	share	total
1 991.7		3	12.0%	4.0%
1 992.6		6	8.0%	12.0%
1 993.5		19	25.3%	37.3%
1 994.4		15	20.0%	57.3%
1 995.3		15	20.0%	77.3%
1 996.2		12	16.0%	93.3%
1 997.1		3	4.0%	97.3%
1 998.0		0	0.0%	97.3%
1 998.9		2	2.7%	100.0%
1 999.8				

d = 1 995.2µm s = 1.60µm N = 75 UGW = 1 992µm OGW = 1 998µm

Wheels

For the optimal moment of inertia to strength ratio, we used the alloy **titanal**, which is easy to manufacture, has a lower density than steel but a better mechanical properties than ordinary aluminium. Furthermore, we invented a technique to reach a **wall-thickness of 0,05mm** of the **wheels rolling-surface**.

Axles

To ensure a **precise and robust bearing fit**, we manufactured our axles out of **titanal** as well. Furthermore, we treat the adhesive area with a sandblaster to improve the glue joint. To improve the fitting of the bearings, we **tested the manufacturing tolerance with an iterative system**.

Hubcap

The wheel caps must be precise to ensure a good and bearing fit. The wheel cap is made out of a **non-particle-based material to protect the bearings**. Moreover, the wheel cap is the socket for the nozzle, a component requiring **a precise mounting**. To **adjust the cars weight** after assembly we chose to manufacture aluminium hubcaps with different wall-thickness iterations.

Workplace safety

- never unsupervised near the machine
- wearing safety glasses and ear protection
- the lathe was always closed while running

Manufacturing constraints

- minimum radius (0.05 mm)
- minimum material thickness (0.04mm)

PRE-ASSEMBLY

To ensure maximal directional stability, the axles must be assembled as parallel as possible. We developed a **steel milled assembly jig** that provides four brackets for the axles. So we are able to glue the axles in the perfect **parallel position** to the car. To check manufacturing tolerances, we measured the parallelism of the axles.

COATING

A coating gives the car a professional finish. From an aerodynamic point of view, the coating of the car should be as **smooth as possible** to reduce **air friction**. Most importantly, it is essential to break no rules due to coating thickness. Therefore we tested in manufacturing prototypes **coating thicknesses** (~ 0.1 mm) to calculate the **correct tolerances**. Despite this testing process, it is still necessary to measure critical locations throughout the coating process to prevent a rule-break. We **outsourced the application of the two final layers** to our sponsor, because these are the **critical layers required for a perfect finish** and you need lots of experience and the right tools to apply them. It is always important to achieve a perfect result while complying with the minimal-mass constraint. The white color and clear coating were done by tielsch und weber.

1. Application of spackling compound on the transitions (SLS-parts)
2. The material of the model block features pores. The sealing of those pores before the real coating is mandatory to prevent the complete absorption of the coating (saving weight). Therefore, we used the "**Glattfix**" **pores filler** combined with sanding in many iterations.
3. Application of primer for the optimal base of the final coating
4. Application of white coating
5. Placing of the **extra-thin decals**
6. Application of clear coating

Workplace safety

- Wearing respirators all the time, handling the coatings or fillers.
- only working in well-ventilated areas

ASSEMBLY

In the final assembly we mount every additional component of the car, under clean-room conditions as follows:

1. Pressing the bearings with special tools into the wheels
2. Attaching the wheels onto the axles
3. Screwing on the wheel caps and securing the position with a special locktide, removing the glue awfterwards is still possible, if needed
4. Gluing the outer wheel cap onto the wheel cap with instant glue
5. Pressing in the tether line guides in the frame and secure them with instant glue to give additional safety
6. Regulation check: **especially tolerances**, fixtures if necessary